Ocean Engineering 89 (2014) 230–242

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# Reliability-based fatigue life investigation for a medium-scale composite hydrokinetic turbine blade

H. Li [a], Z. Hu [a], K. Chandrashekhara [a,*], X. Du [a], R. Mishra [b]

[a] Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA
[b] Department of Materials Science and Engineering, University of North Texas, Denton, TX 76203, USA

ARTICLE INFO

*Article history:*
Received 16 October 2013
Accepted 8 August 2014
Available online 6 September 2014

*Keywords:*
Fatigue
Reliability
Blade element momentum
Finite element method
Hydrokinetic
Composite blade

ABSTRACT

As the most important, expensive component of a hydrokinetic turbine system, the composite turbine blade must achieve a long operating life (10–20 years). The investigation of fatigue life for the composite turbine blade is essential when designing a cost-effective hydrokinetic composite turbine system. A reliability-based fatigue life analysis methodology was developed for a medium-scale, horizontal axis, hydrokinetic turbine blade. Finite element method, coupled with the blade element momentum theory, was used to find the stress response on the turbine blade. The fatigue behavior of the blade was studied in stress-critical zones. A metamodel was constructed for the stress response according to simulations at specified design points. Accounting for uncertainties in material properties and the material *S–N* curve, the reliability analysis method was employed to estimate the fatigue life distribution of the hydrokinetic turbine blade. The effect of river velocity models on the fatigue life of turbine blades was also studied. The fatigue life of the composite blade was sensitive to composite material properties. Transverse strain $E_{22}$ is particularly dominant which is related to the matrix cracking as the fatigue failure mode. The statistical distribution of *S–N* data implies a significant dependence of fatigue life on composite *S–N* data.
© 2014 Elsevier Ltd. All rights reserved.

## 1. Introduction

Hydrokinetic turbines contribute to zero-head hydropower. The turbines use hydrokinetic power from flowing water to generate power. In many ways, hydrokinetic turbines resemble wind turbines. The most notable difference is in density; the density of water is approximately 850 times greater than the density of air. Thus, more energy is expected from a hydrokinetic turbine. Due to the vast resources of hydrokinetic/tidal energy on earth the research into hydrokinetic/tidal turbine systems, as an alternative renewable energy, has been booming in recent years (Khan et al., 2009; Schwartz, 2006).

The blade is the key component in a hydrokinetic turbine system; it determines the performance of the turbine system. A hydrodynamic profile design of the turbine blade is required to extract the maximum energy from water flow. Environmental conditions must be considered when designing the blade. Varying hydrokinetic loadings, water/mud corrosion and impact from floaters and fish schools each has a significant effect on the blade's operating life. From a structural point of view: (1) the hydrokinetic turbine blade is long and flexible; (2) there are possibilities of vibrations in the resonant mode; (3) the randomness of water velocity causes randomness of load spectra; and (4) low maintenance is expected during operating under water with different conditions (Shokrieh and Rafiee, 2006). Load identification, geometry/structural design, static failure, and fatigue failure all need to be addressed to create a successful blade design.

Typical fatigue loads on hydrokinetic turbine blades include stochastic hydrodynamic loadings from water streams, weight and buoyancy of the composite blade, and induced centrifugal and coriolis force (Nijssen, 2006). The stochastic hydrokinetic loadings include the flapwise loads and the edgewise loads. The flapwise loads originate primarily from the water load. This load acts perpendicular to the rotor plane. The edgewise loads originate primarily from the blade weight, buoyancy forces from water volumes occupied by the blade body, and also the torque loads that drive the rotor. The loading direction for edgewise loads changes twice during a revolution.

As regards materials, attractive characteristics of composites like light weight, high strength/stiffness, design flexibility and corrosion resistance (as compared to metallic materials) make composite materials an advantageous option for river applications. Based on these characteristics of composites, manufacturing using composites is capable of achieving a structural design with a complicated geometric layout and adequate load-carrying capacity while achieving significant weight reduction.

* Corresponding author. Tel.: +1 573 341 4587.
*E-mail address:* chandra@mst.edu (K. Chandrashekhara).

http://dx.doi.org/10.1016/j.oceaneng.2014.08.006
0029-8018/© 2014 Elsevier Ltd. All rights reserved.

The manufacturing process for composite structures is quite complex. As a result, various parameters can influence the fatigue behavior of composites in terms of fiber/matrix type, reinforcement structure, laminate stacking sequence, environmental conditions (both temperature and moisture), and loading conditions (stress ratio, frequency) (Degrieck and Paepegem, 2001). The damage accumulation of composites from these factors may either independently or interactively affect fatigue life. Over the last several decades, various fatigue damage models of fiber reinforced composite materials have been developed. These models can be mainly categorized into three sections: (1) *S–N* curves/Goodman diagrams incorporating fatigue failure criterion with no degradation mechanisms, (2) phenomenological models based on residual stiffness/strength, and (3) progressive damage models utilizing damage variables to characterize different damage mechanisms (e.g. matrix cracks and delamination). Detailed discussions on the development of fatigue damage models of fiber-reinforced composite materials can be found in review papers (Degrieck and Paepegem, 2001; Post et al., 2008).

The fatigue life of composites for wind turbine blade applications has been studied considerably as a result of the rapid growth in the wind industry. A Department of Energy/Montana State University (DOE/MSU) composite material fatigue database for wind blades (Mandell and Samborsky, 2010) was established under sponsorship of Sandia National Laboratories (SNL). The database includes detailed fatigue results for composite materials under constant/variable amplitude fatigue loadings. Sutherland and Mandell (2005a, 2005b) studied the effect of both mean stress and an optimized constant-life diagram on the damage of wind turbine blades. Samborsky et al. (2008) investigated the fatigue loading effect on delamination at thick ply drops in both carbon and glass fiber laminates. Comparatively, study regarding composites used for hydrokinetic/tidal applications is still much less. Some preliminary studies can be seen in Mahfuz and Akram (2011), Kennedy et al. (2011), and Li et al. (2012).

Fatigue loads on hydrokinetic turbine blades have a certain degree of statistical variability. These factors comprise material variability, variable water velocity, and scattered *S–N* data. Young et al. (2010) quantified the influence of material and operational uncertainties on the performance of self-adaptive marine rotors. A reliability based design and optimization methodology for adaptive marine structures was developed. Lange (1996) found that fatigue reliability is significantly dependent on the type of model chosen. An increasing spread in failure probabilities for a given turbine life was observed in flatter *S–N* curves. Blade-to-blade variation has been characterized very little due to the complexity of composite manufacturing processes (Nijssen, 2006). Hence, the reliability method should be introduced into the fatigue analysis of composite blades.

The study on composite blades for hydrokinetic applications is very limited and there is a lack of complete characterization of factors' effect (material, flow, and fatigue data) on the fatigue life. The purpose of this paper is to quantify the effects of material, loading uncertainties on the stress response and fatigue data on the fatigue life distribution of a medium-scale hydrokinetic composite turbine blade. The optimized composite turbine blade is intended to be deployed in Missouri River. A fully-coupled blade element momentum-finite element method (BEM-FEM) was used to compute the stress response of the turbine blade. Modeling uncertainties were conducted with the Hashin failure initiation model to correlate with the fatigue failure mode of the turbine blade. The fatigue model was based on both MSU/DOE experimental *S–N* data and the residual strength approach to cumulative damage. The probability of fatigue failure was evaluated. The effects of the river flow velocity model were investigated on the fatigue probability distribution of the turbine blade.

## 2. Structural design of the composite blade

### 2.1. Hydrodynamic profile

The composite blade was designed for three-blade, horizontal axis, hydrokinetic turbine systems. It has a length of 1 m, and varying cross sections with an 8° twist angle. The circular root section was designed for easy mounting on the hub. The blade consisted of eight blade stations, as shown in Fig. 1. The blade profile was based on hydrofoil Eppler 395. The hydrofoil provides a high ratio of $C_l/C_d$. Detailed identification of both the hydrodynamic profile and the corresponding hydrodynamic loadings on the blade surface, with varying tip speed ratio (TSR), is illustrated in Section 3.

### 2.2. Facesheet and core materials

Hydrokinetic turbine systems operating under water experience highly repetitive hydrodynamic loadings. Also, bio-fouling and corrosion issues need to be addressed properly. The hydrokinetic turbine blade facesheet made of composite materials with a high modulus and strength provides excellent static failure resistance. Corrosion issues can also be effectively prevented with the use of composite materials (Anyi and Kirke, 2010). Widely used carbon fibers normally cost 10–20 times as much as glass fibers. Carbon fibers do, however, provide a much higher modulus and weight reduction. An E-glass/epoxy material was selected as a compromise between price and performance. Initial work on the blade design was conducted based on both trial and error and numerical optimization methods (Li and Chandrashekhara, 2012). In the current study, E-glass/epoxy laminates with $[0_2/90_2/0_2/90_2]$ ply orientations were used to form the facesheet of the hydrokinetic turbine blade. Each ply thickness was 0.356 mm.

Various blade core configurations were evaluated to obtain an optimal blade internal structural layout (Berry, 2007): hollow, solid foam, composite shear web, and both foam and shear web, as illustrated in Fig. 2. Blades with a facesheet tend to provide only the lightest solution when operating under water. Water impermeability is prevented as water is prone to intrude the cavity of the blade. The water intrusion causes extra dynamic loadings when the blade rotates and significantly reduces the fatigue life of the blade. The core material selected requires high buckling resistance, water impermeability, and high strength to weight ratios. Divinycell HCP 100 was selected to provide excellent hydraulic compressive properties, a closed cell structure with very low buoyancy loss, and water absorption under long-term loading conditions. Moreover, HCP 100 offers excellent ductile characteristics; it is suitable for hydrokinetic turbine blades which experience either impact or slamming loads from floaters and schools of fish. Given the water impermeability of the turbine blade, the weight of the turbine blade tends to be offset by neutral buoyancy. The buoyancy from the core material is beneficial for a fatigue load reduction of the rotor and a higher power extraction from water. However, it seems insufficient with only solid foam to withstand shear loading. Thus, the concept of a shear web was introduced. Therefore solid foam, combined with a shear web, was adopted for the blade core design to provide water impermeability and maintain a shear loading capacity.

### 2.3. Failure mode of the composite blade

An appropriate damage initiation model must be chosen to evaluate the failure mode of the composite blade. Unlike maximum stress/strain, the Tsai–Hill and Tsai–Wu criterion, Hashin damage considers four different failure modes: fiber tension, fiber compression, matrix tension, and matrix compression. Failure in the ply thickness direction is ignored. Hashin damage predicts the dominating factor that influences the cracking/failure of the composite blade. Predictions from Hashin damage were used in

Download English Version:

https://daneshyari.com/en/article/8066319

Download Persian Version:

https://daneshyari.com/article/8066319

Daneshyari.com